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Technical Note

Quantitative estimation of joint roughness coefficient using statistical parameters

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1. Introduction

The rock joint roughness coefficient (*JRC*) has been used for the estimation of the peak shear strength of rock joints since 1973 when Barton [1] put forward the following empirical equation, which is also called JRC–JCS model:

$$\tau = \sigma \tan\left[JRC \log(JCS/\sigma) + \varphi_b\right] \quad (1)$$

where τ is the peak shear strength of the rock joint, σ is the normal stress, JRC is the joint roughness coefficient, JCS is the strength of joint wall, φ_b is the basic friction angle. Over the last half century, researchers have kept working on techniques for estimating JRC of rock joints for or from this model. So far, the JRC value of a particular rock joint is most often estimated by visibly comparing it to the ten standard profiles with JRC values ranging from 0 to 20 [2]. This method was also adopted by the ISRM commission on test methods since 1981 [3]. In rock engineering practice, however, the visible comparison has been long thought to be subjective in that the user has to judge which profile his joint fits the best. The development of objective methods was gradually advanced by researchers considering quantitative estimation.

Tse and Cruden [4] established regression correlations between JRC and Z_2 (the root mean square of the first deviation of the profile) proposed by Myers [5] and *SF* (the structure function) by Sayles and Thomas [6]. As Tse and Cruden's equations have correlation coefficients as big as 0.986, they are often employed to estimate JRC [7,8], though Z_2 and *SF* were later found by Yu and Vayssade [9] and Yang et al. [10] to be sensitive to the sampling interval. Yu and Vayssade [9] argued that Tse and Cruden's preparation of the discrete point data was improper, as an isotropic transformation (enlarging the standard profiles by 2.5 times both in *x*- and *y*-coordinates) may exaggerate the roughness of the joint profiles. They manually digitized the ten standard profiles at three different sampling intervals of 0.25, 0.5 and 1.0 mm and indicated strong influences of sampling interval on JRC estimated by Tse and Cruden's equations. Yang et al. [10] reconstructed the ten standard profiles by means of Fourier transform and updated the correlations between JRC and Z_2 as well as *SF*. Their equations display even higher correlation coefficients (0.99326) (Table 2).

Besides Z_2 and *SF*, R_p was also taken as one of the parameters to estimate JRC of a rock joint. R_p was firstly defined as roughness profile index by El-Soudani [14], which is equal to the ratio of the true length of a fracture surface trace to its projected length in the fracture plane. Maerz et al. [12] employed the ten standard profiles and related their JRCs to R_p, which gave a linear relationship with a correlation coefficient of 0.984. Yu and Vayssade [9] also proposed to estimate JRC using *RL*. Though *RL* was considered by Yu and Vayssade [9] as “real profile length”, the authors found it is identical to R_p according to its calculation provided in Yu and Vayssade's appendix.

Wang [13] derived an empirical equation with *R* as the parameter to estimate *JRC*, where *R* was called as “elongation rate” and

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Table 1
Unification of definitions and symbols in empirical equations.

Unified term	Definition	Unit	Calculation	Original	References
R_p	Roughness profile index	–	$R_p=L_t/L$ $L_t=\sum_{i=1}^{N-1}\sqrt{(x_{i+1}-x_i)^2+(y_{i+1}-y_i)^2}$ $L=\sum_{i=1}^{N-1}(x_{i+1}-x_i)$	RL R_p	Yu and Vayssade [9] Tatone and Grasselli [11]
δ	Profile elongation index	–	$\delta=(L_t-L)/L$	$RL1$ $Rp-1$	Yu and Vayssade [9] Maerz et al. [12]
δ_L	Profile elongation rate	–	$\delta_L=\delta\times 100$	R	Wang [13]
λ	Ultimate slope of the profile	–	$\lambda=R_z/L$	a/L	Barton and de Quadros [15]
R_a	Arithmetical mean deviation roughness index of the profile	mm	$R_a=\frac{1}{L}\int_{x=0}^{x=L}\lvert y\rvert dx=\frac{1}{L}\sum_{i=1}^{N-1}\lvert y_i\rvert\Delta s$	CLA	Tse and Cruden [4]
R_q	Root mean square roughness index of the profile	mm	$R_q=\left[\frac{1}{M}\int_{x=0}^{x=M}y^2\,dx\right]^{1/2}$ $=\left[\frac{1}{M}\sum_{i=1}^{N-1}y_i^2\Delta s\right]^{1/2}$	RMS	Tse and Cruden [4]
M_s	Mean square value roughness index	mm^2	$M_s=\frac{1}{L}\int_{x=0}^{x=L}y^2\,dx=\frac{1}{L}\sum_{i=1}^{N-1}y_i^2\Delta s$	MSV	Tse and Cruden [4]
Z_2	Root mean square of the first deviation of the profile	–	$Z_2=\left[\frac{1}{L}\int_{x=0}^{x=L}\left(\frac{dy}{dx}\right)^2dx\right]^{1/2}$ $=\left[\frac{1}{L}\sum_{i=1}^{N-1}\frac{(y_{i+1}-y_i)^2}{x_{i+1}-x_i}\right]^{1/2}$	Z_2	Tse and Cruden [4] Yu and Vayssade [9] Yang et al. [10] Tatone and Grasselli [11]
σ_i	Standard deviation of the angle i	–	$\sigma_i=\tan^{-1}\left[\frac{1}{L}\int_{x=0}^{x=L}\left(\frac{dy}{dx}-\tan\ i_{ave}\right)^2dx\right]^{1/2}$ $i_{ave}=\frac{1}{L}\int_{x=0}^{x=L}\tan^{-1}\left(\frac{dy}{dx}\right)dx$	SD_i	Yu and Vayssade [9]
SF	Structure function of the profile, equals to $(Z_2\Delta x)^2$	mm^2	$SF=\frac{1}{L}\int_{x=0}^{x=L}[f(x+dx)-f(x)]^2dx$ $=\frac{1}{L}\sum(y_{i+1}-y_i)^2\Delta x$	SF	Tse and Cruden [4] Maerz et al. [12] Yu and Vayssade [9] Yang et al. [10]

Notation: dx – increment of x of the profile; dy – increment of y of the profile; N – number of evenly spaced sampling points; M – number of sample intervals; L – projected length of the profile, the length along abscissa; L_t – true length of the profile; Δs – sampling interval; R_z – maximum height of the profile, equals to the vertical distance between the highest peak and the lowest valley.

defined as the percentage of the difference between the true length and the projected length to the projected length of a profile. Besides Z_2 and SF, R_p, RL and R mentioned above, other parameters have also been suggested for JRC estimation. Examples are Yu and Vayssade's SD_i and $RL1$, Tse and Cruden's RMS, CLA and MSV, and Barton and de Quadros's a/L. Among these parameters, SD_i was found to have the closest correlation with JRC. The definition of these parameters can be found in Table 1 of this paper.

So far, all the above-mentioned empirical equations were highly cited in both academic research and engineering practice. However, these equations were, with no exception, based merely on the ten standard profiles. In other words, they were based exclusively on 10 data points, which is considered insufficient for a reliable correlation. In addition, these equations differ tinily from one another in terms of correlation coefficient, leading to difficulties when ranking the suitability of them and choosing one to use in engineering practice. Last but certainly not least, the terms, symbols and even calculation formulae of the parameters in these equations are never unified but conflicting sometime.

Bearing in mind the above, this study aims to (1) summarize the existing empirical equations; (2) normalize the symbols and/or abbreviations used in these equations; and (3) calibrate the empirical equations by using a big population of rock joint profiles.

2. Normalization of symbols

As stated in the previous section, the symbols, even for the same parameter used in the literature, are various from one author to another, lowering the readability. Table 1 lists the parameters together with their definitions, calculation formulae and symbols originally appeared in the literature. The unified symbol is assigned in the first column to each parameter by taking reference to the related international standards [16,17]. The column “Original” provides the symbols used by authors in column “References”.

Such a summary and normalization in Table 1 is considered useful in that one can easily understand the definition of each parameter, avoiding extraordinary efforts to review the long and complicated portfolio like what the authors have done. The calculation is given in both integral and explicit summation forms, favoring an easy calculation of a discrete data set. The unified symbols and abbreviations rather than their original version are used in the following discussion.

3. Empirical equations in the literature

Table 2 lists the retrievable equations in the literature for the estimation of JRC of a joint profile. Totally, 47 equations were collected, of which 19 correlations take Z_2 as parameter; 8 take SF; 5 take R_p; 6 take σ_i; 4 take δ; and the others take δ_L, R_q, R_a, M_s, and λ, respectively for each.

According to Table 2, the following two observations can be made:

1) The correlation coefficients for these equations are generally greater than 0.90 except for R_q (0.784), R_a (0.768) and M_s (0.690). Among them, the equations with Z_2 and SF by Yang et al. [10] have the highest correlation coefficient of 0.993.
2) According to the definition, when JRC of 0 represents a planar joint (a saw-cut profile, for instance), Z_2, δ_L, R_q, R_a, δ and M_s should be 0 and R_p be 1. However, as shown in column “JRC^0”, only Eqs. (30) [12] and (47) [15] are capable of estimating JRC of

Table 2
Literature review of empirical equations for estimating JRC.

No.	Equation	R	SI (mm)	JRC[a]	Range[b]	Reference
1	$JRC=32.2+32.47\ \log(Z_2)$	0.986	1.27	–	0.1019–04210	Tse and Cruden [4]
2	$JRC=-4.41+64.46\ Z_2$	0.968	1.27	−4.41	0.0684–0.3787	
3	$JRC=-5.05+1.20\ \tan^{-1}(Z_2)$	0.973	1.27	−5.05	0.0736–0.3814	
4	$JRC=32.69+32.98\ \log(Z_2)$	0.993	0.5	–	0.1020–0.4123	Yang et al. [10]
5	$JRC=60.32Z_2–4.51$	0.968	0.25	−4.51	0.0748–0.4063	Yu and Vayssade [9]
6	$JRC=64.28\ \tan(Z_2)-5.06$	0.969	0.25	−5.06	0.0768–0.317	
7	$JRC=116.3(Z_2)^2–2.30$	0.929	0.25	−2.3	0.1460–0.4379	
8	$JRC=56.15\sqrt{Z_2}-16.99$	0.967	0.25	−16.99	0.0916–0.4108	
9	$JRC=28.10\ \log(Z_2)+28.43$	0.951	0.25	–	0.0973–0.5012	
10	$JRC=61.79Z_2–3.47$	0.973	0.5	−3.47	0.0562–0.3798	
11	$JRC=65.18\ \tan(Z_2)-3.88$	0.975	0.5	−3.88	0.0595–0.3512	
12	$JRC=130.87(Z_2)^2–2.73$	0.934	0.5	−2.73	0.1444–0.4168	
13	$JRC=54.42\sqrt{Z_2}-14.83$	0.973	0.5	−14.83	0.0743–0.4096	
14	$JRC=25.57\ \log(Z_2)+28.06$	0.954	0.5	–	0.0799–0.4839	
15	$JRC=64.22Z_2–2.31$	0.983	1.0	−2.31	0.0360–0.3474	
16	$JRC=66.86\ \tan(Z_2)-2.57$	0.983	1.0	−2.57	0.0384–0.3256	
17	$JRC=157(Z_2)^2–3.00$	0.945	1.0	−3	0.1382–0.3827	
18	$JRC=51.85(Z_2)^{0.60}–10.37$	–	0.5	−10.37	0.0684–0.4100	Tatone and Grasselli [11]
19	$JRC=55.85(Z_2)^{0.74}–6.10$	–	1.0	−6.1	0.0512–0.3649	
20	$JRC=37.63+16.5\ \log(SF)$	0.993	0.5	–	0.0052–0.0854	Yang et al. [10]
21	$JRC=2.69+245.70SF$	0.919	1.27	2.69	0–0.0705	Tse and Cruden [4]
22	$JRC=37.28+16.58\ \log(SF)$	0.984	1.27	–	0.0056–0.0907	
23	$JRC=239.27\sqrt{SF}-4.51$	0.968	0.25	−4.51	0.0004–0.0105	Yu and Vayssade [9]
24	$JRC=14.05\ \log(SF)+45.25$	0.951	0.25	–	0.0006–0.0160	
25	$JRC=121.13\sqrt{SF}-3.28$	0.972	0.5	−3.28	0.0007–0.0369	
26	$JRC=12.64\ \log(SF)+35.42$	0.954	0.5	–	0.0016–0.0603	
27	$JRC=10.66\ \log(SF)\ +26.49$	0.950	1.0	–	0.0033–0.2461	
28	$JRC=\left(0.036+\frac{0.00127}{\ln(R_p)}\right)^{-1}$	–	0.5	–	1.0013–1.0950	Tatone and Grasselli [21]
29	$JRC=\left(0.038+\frac{0.00107}{\ln(R_p)}\right)^{-1}$	–	1.0	–	1.0013–1.1116	
30	$JRC=411\delta$	0.984	0.684	0	0–0.0487	Maerz et al. [12]
31	$JRC=558.68\sqrt{R_p}-557.13$	0.951	0.25	1.55	1–1.0671	Yu and Vayssade [9]
32	$JRC=559.73\sqrt{R_p}-597.46$	0.945	0.5	−37.73	1.1394–1.2169	
33	$JRC=702.67\sqrt{R_p}-599.99$	0.951	1.0	102.68	1–0.7785	
34	$JRC=92.97\sqrt{\delta}-5.28$	0.971	0.25	−5.28	0.0032–0.0739	
35	$JRC=92.07\sqrt{\delta}-3.28$	0.974	0.5	−3.28	0.0013–0.0639	
36	$JRC=63.69\sqrt{\delta}-2.31$	0.982	1.0	−2.31	0.0013–0.1227	
37	$JRC=\log(\delta_L)/\log(1.0910216)$	–	–	–	1.000–5.7104	Wang [13]
38	$JRC=2.37+70.97R_q$	0.784	1.27	2.37	0–0.2484	Tse and Cruden [4]
39	$JRC=2.76+78.87R_a$	0.768	1.27	2.76	0–0.2186	
40	$JRC=5.43+293.97M_s$	0.690	1.27	5.43	0–0.0496	
41	$JRC=1.12\sigma_i-5.06$	0.969	0.25	−5.06	4.5179–22.3750	Yu and Vayssade [9]
42	$JRC=1.14\sigma_i-3.88$	0.975	0.5	−3.88	3.4035–20.9747	
43	$JRC=1.17\sigma_i-2.57$	0.983	0.1	−2.57	2.1966–19.2906	
44	$JRC=7.74\sqrt{\sigma_i}-17.83$	0.966	0.25	−17.83	5.3067–23.8886	
45	$JRC=7.36\sqrt{\sigma_i}-15.08$	0.970	0.5	−15.08	4.1980–22.7717	
46	$JRC=6.95\sqrt{\sigma_i}-12.14$	0.976	0.1	−12.14	3.0512–21.3856	
47	$JRC=400\lambda$	–	–	0	0–0.0500	Barton and de Quadros [15]

Note: Data by Tse and Cruden were from profile magnified by 2.5× in both x and y directions. R – correlation coefficient; SI – sampling interval.

[a] JRC – estimated JRC value for a truly smooth plane;

[b] Range – applicable range of independent value.

a planar or truly smooth profile ($\delta=0$, $\lambda=0$). The rest equations normally give a substantial JRC value or even derive a negative JRC value (e.g. Eqs. (2) [4], (3) [4], (5) [9], (6) [9] and (8) [9], etc.) for a smooth plane.

Considering no proposer has provided the limitation of his correlation/s, this study delineates the acceptable range of the independent value for each equation to be logically used (in column “Range”). Bearing this in mind, the users are highly suggested to be cautious when using these equations for relatively planar and inerratic profiles.

The data point retrieved from the literature are digitized and replotted in terms of independent in Fig. 1 together with the correlations listed in Table 2. It can be seen that (1) in the case of Z_2 (Fig. 1a), the existing equations show a consistent pattern to some extent, especially in the middle section with Z_2 between 0.15 and 0.3. Eq. (12) [9] escapes from the main trend and would give JRC estimations with non-ignorable errors. The nonlinear correlations (Eqs. (11) and (14) [9]) show obvious variations, especially in both ends of the estimation. (2) For SF (Fig. 1b), the correlations (Eqs. (25) and (26)) proposed by Yu and Vayssade [9] vary at the upper end, though they both have correlation coefficients greater than 0.95. (3) In the case of R_p (Fig. 1c), Eqs. (28) [21], (30) [12] and (35) [9] show a good consistence, except for variation in the upper part. Eq. (32) by Yu and Vayssade [9], however, lies far away from the main trend. This might be a writing mistake. The authors take regression on Yu and Vayssade's data, which gives a corrected version for Eq. (32) [9] as $JRC=579.89R_p+557.76$. (4) for σ_i (Fig. 1e),

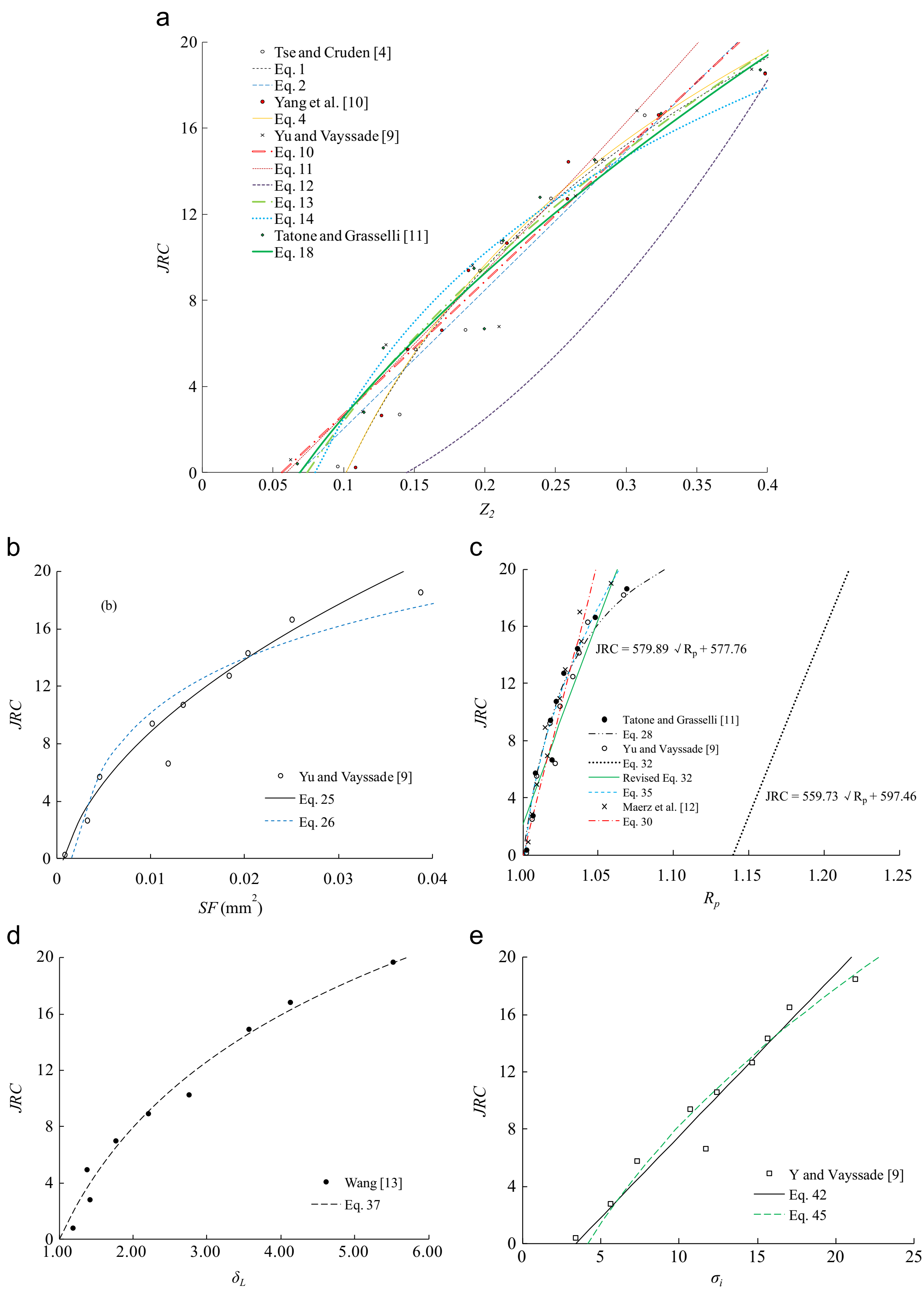

Fig. 1. Empirical relationships in literature for estimating JRC by means of (a) Z_2; (b) SF; (c) R_p; (d) δ_L; and (e) σ_i. Equations refer to Table 2.

Eqs. (42) and (45) [9] exhibit differences at the upper end. (5) Last but the most important, all the equations in Fig. 1 and Table 2 were derived merely from data points of the ten standard profiles proposed by Barton and Choubey [2]. The authors consider the number of data points is insufficient for deriving a reliable and sophisticated relationship.

4. Data set preparation

In addition to the ten standard profiles, this study makes use of another 102 profiles from the literature. Among them, 12 profiles are from Grasselli [18], 26 are from Bandis et al. [19] and the rest (64) from Bandis [20]. The JRC values of the chosen profiles were

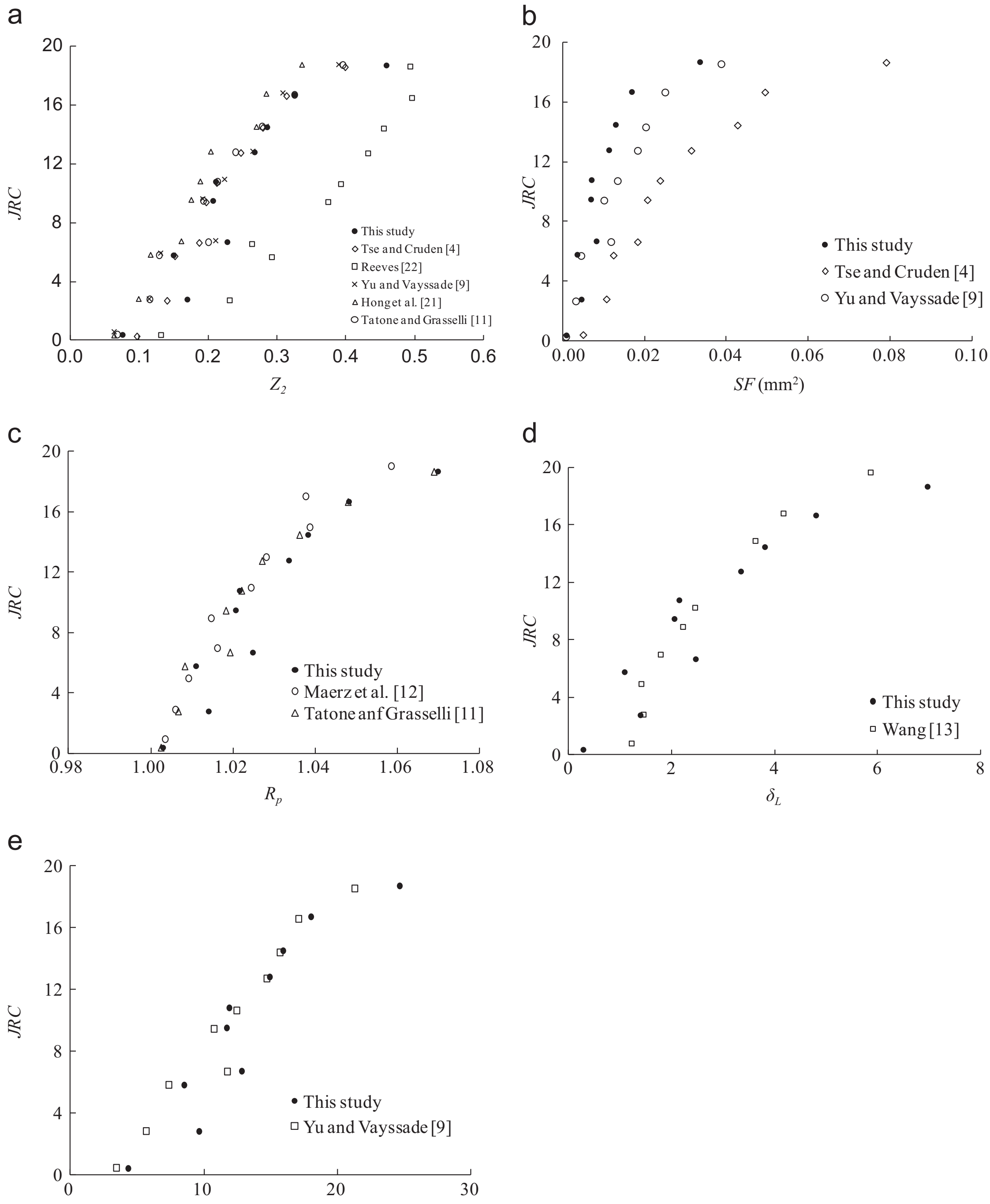

Fig. 2. Data points of the ten standard profiles by different authors: (a) Z_2; (b) SF; (c) R_p; (d) δ_L; and (e) σ_i.

Table 3
JRC values of the ten standard profiles used in literature for deriving equations in Table 2.

Standard JRC profiles	1	2	3	4	5	6	7	8	9	10
JRC values recommended by Barton and ISRM	0–2	2–4	4–6	6–8	8–10	10–12	12–14	14–16	16–18	18–20
Maerz et al. [12] and Wang [13]	1	3	5	7	9	11	13	15	17	19
Others	0.4	2.8	5.8	6.7	9.5	10.8	12.8	14.5	16.7	18.7

originally determined by back calculation of direct shear tests on rock joint with the JRC–JCS shear strength model. The projected length of the 112 profiles ranges from 72 to 119.6 mm, and the JRC values range from 0.4 to 20. The rocks these joint profiles come from cover a wide variety of rock types, including sandstone, limestone, marble, granite, gneiss, slate, dolerite and siltstone of various weathering degrees (fresh, slightly weathered and moderately weathered). These joints are tension fractures and vary from well interlocked planar cleavage fractures to poorly interlocked film-covered walls.

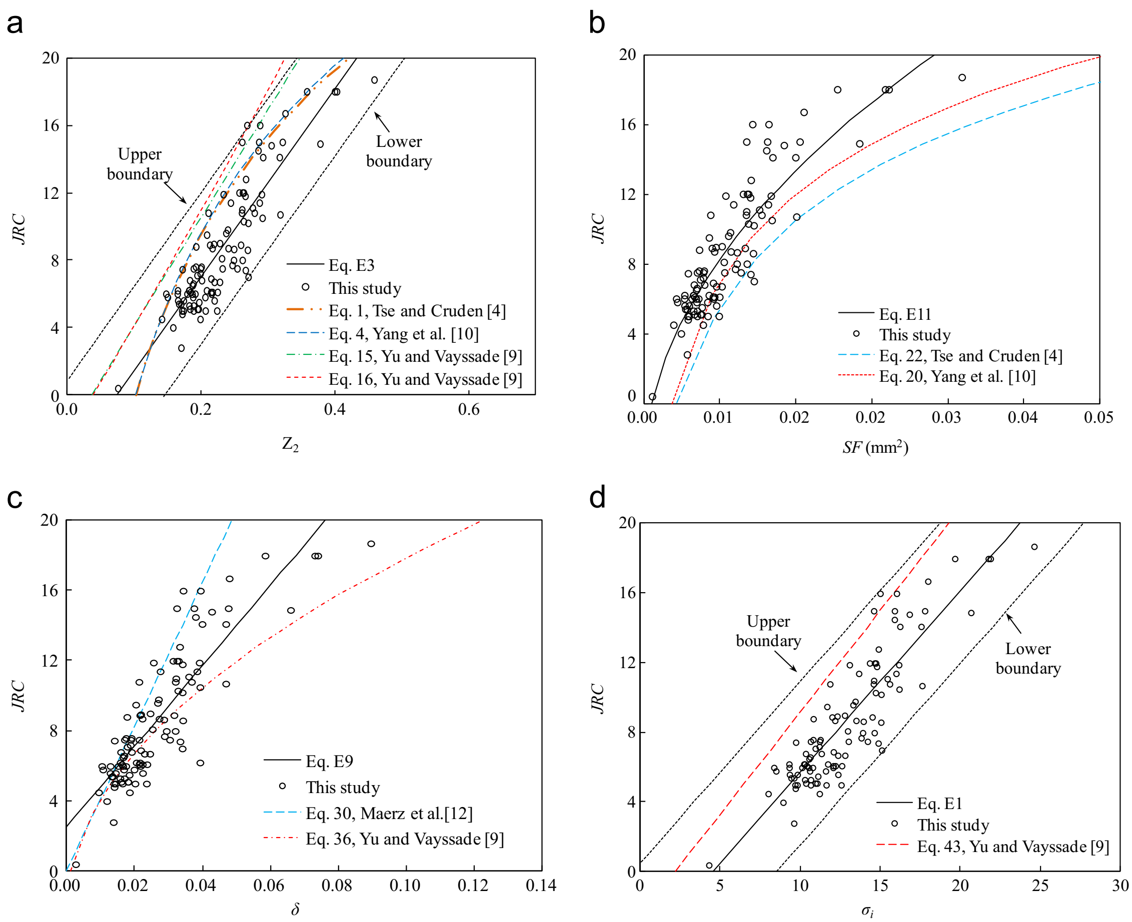

Fig. 3. Comparison between current and previously published equations: (a) Z_2; (b) SF; (c) δ; and (d) σ_i.

Table 4
Empirical equations derived from this study for JRC estimation.

No.	Variable	Equation	R	JRC^0	Rang#
E1	σ_i	$JRC = 1.0419\sigma_i - 4.7334$	0.8843	−4.7334	4.523–23.740
E2		$JRC = 0.0950\sigma_i^{1.7484}$	0.8780	0	0–21.313
E3	Z_2	$JRC = 55.7376Z_2 - 4.1166$	0.8843	−4.1166	0.074–0.433
E4		$JRC = 98.718Z_2^{1.6833}$	0.8760	0	0–0.387
E5	R_z	$JRC = 1.5715R_z + 4.0318$	0.8608	4.0318	0–10.161
E6		$JRC = 4.4192\ R_z^{0.6482}$	0.8089	0	0–10.269
E7	λ	$JRC = 158.7575\lambda + 3.9076$	0.8561	3.9076	0–0.101
E8		$JRC = 89.9971\lambda^{0.6601}$	0.8124	0	0–0.102
E9	δ	$\mathrm{JRC} = 229.44\delta + 2.5043$	0.8603	2.5043	0–0.076
E10		$\mathrm{JRC} = 199.6443\delta^{0.8665}$	0.8707	0	0–0.070
E11	SF	$\mathrm{JRC} = 137.1739\sqrt{\mathrm{SF}} - 3.9998$	0.8725	−3.9998	0.001–0.031
E12	R_q	$\mathrm{JRC} = 10.9577\ \log(R_q) + 11.5207$	0.8735	–	0.089–5.941
E13	M_s	$\mathrm{JRC} = 2.3794\ \ln(M_s) + 11.5207$	0.8735	–	0.008–35.291
E14	R_a	$\mathrm{JRC} = 10.5953\ \log(R_a) + 12.357$	0.8664	–	0.068–5.265
E15	R_p	$\mathrm{JRC} = 229.44R_p - 226.9357$	0.8603	2.5043	1.0–1.076

As there were no available digital data of the employed profiles, the images of these profiles in the original publications in PDF format are imported into AutoCAD. The dimension system of AutoCAD was configured to meet each image by referencing to the scale bar on the original image. A set of vertical lines spaced 0.4 mm apart were constructed across the length of the profiles and polylines were used to trace the profiles with the intermediate points falling on the intersections of the vertical lines with the profile. Once each profile was traced, the coordinates defining the polylines were exported to an ASCII file.

It should be noted that some error may be introduced by the above data processing, as this process indeed re-samples the profile which is essentially a re-sampling of the original joint profile. The digitized points of the profiles considered in this study along with the associated back-calculated JRC values are supplemented as an electronic resource to this paper. Researchers may make use of them for future investigation without further degradation of the quality of data source.

Following digitization of the profiles, it was noted that the original profiles were not aligned such that the average plane (best-fit straight line) was horizontal. Instead, the best-fit line through all profiles had a non-zero overall slope. This was also found by Tatone and Grasselli [11]. To make the profiles horizontally aligned trend removal was conducted by utilizing a computer program written by the authors. The other function of this computer program is to perform data validation and calculation of profile roughness parameters according to the formulae in Table 1.

5. Discussion

5.1. The ten standard profiles

The previously published values of Z_2, SF, R_p, δ_L and σ_i for each standard profile and those from the present study are plotted in Fig. 2a–e, respectively. As indicated by the plots, the data from the

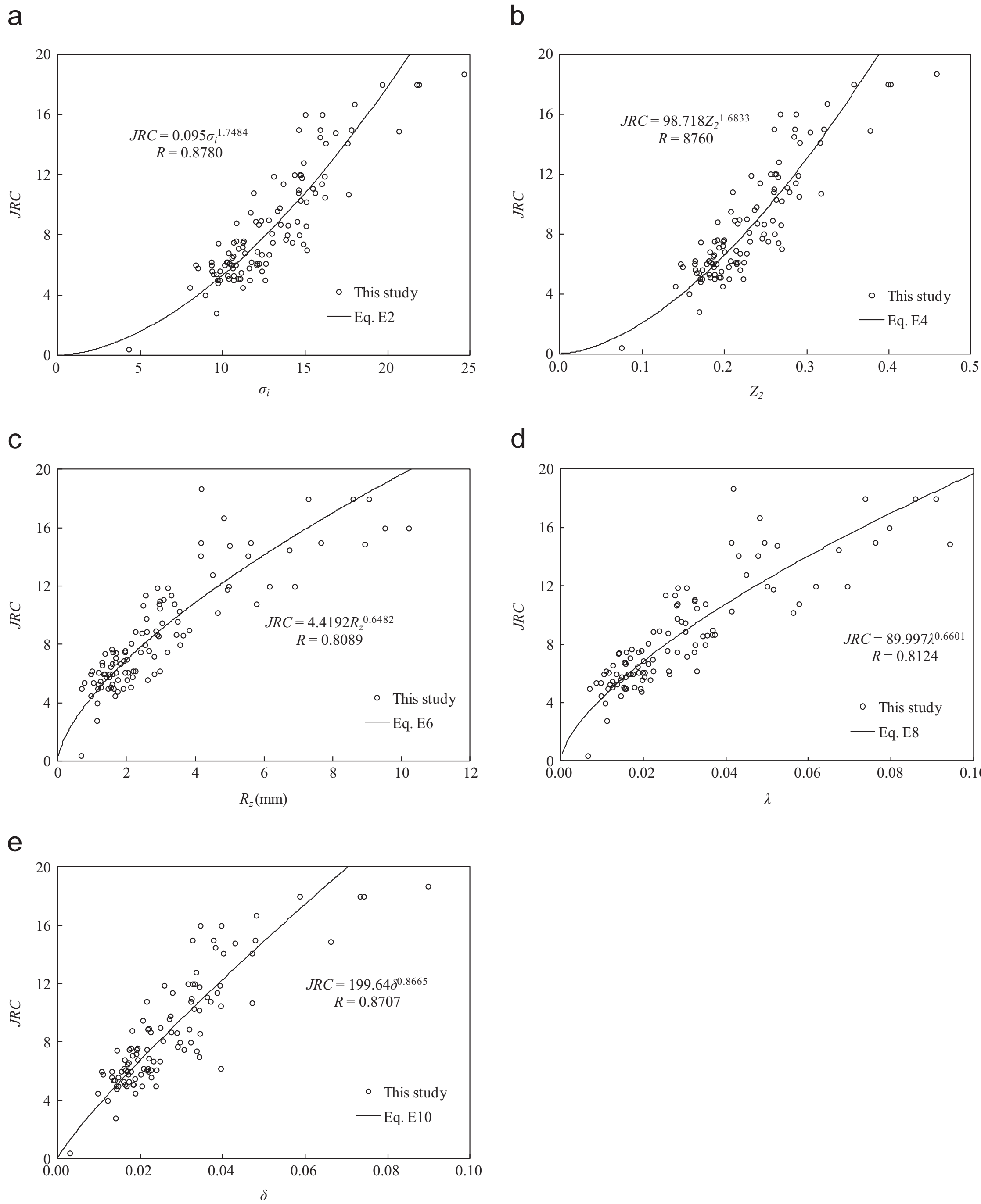

Fig. 4. Equations applicable for planar or sub-planar joint profiles: (a) σ_i; (b) Z_2; (c) R_z; (d) λ; and (e) δ.

current study are falling into the same main trend as the previously published values. However, it is still obvious that differences do exist from author to author though they used the same processing sequence and similar sampling interval. R_p, δ_L and σ_i show a relatively consistent increasing pattern with JRC (Fig. 2c–e), while Z_2 and *SF* by a researcher may totally separate from other originalities (Fig. 2a and b). For Reeves's [22] data shown in Fig. 2a, we could not find any other reasons but he might have employed a wrong calculation for his Z_2. *SF* in Fig. 2b exhibits evident uncertainty at the upper end. As defined in Table 1, *SF* equals to $(Z_2\Delta x)^2$ and it is strongly dependent on the sampling interval [9]. Little bias in sampling interval during operation might exaggerate the variation of the calculated *SF*, though the sampling interval of the plotted data were all claimed to be 0.5 mm.

After a careful verification, it is found that the JRC value for each standard profile was inconsistently assigned in the literature. As shown in Table 3, Maerz et al. [12] and Wang [13] took the intermediate odd numbers (i.e., 1, 3, 5, etc.) as the JRC value of the standard profiles, while other researchers used the values by Barton and Choubey [2]. This would certainly lead to deviation not only in the plots but also in the derived empirical equations. The JRC values by Barton and Choubey [2] were used in the present study since they were directly back-calculated from direct shear tests.

5.2. New empirical equations

The results of Z_2, SF, δ and σ_i for the retrieved 112 profiles are plotted against JRC values in Fig. 3a–d. For the profile which comes with a unique JRC value, the value was used directly. For the profile which comes with a range of JRCs, (e.g., profiles from Bandis et al. [19]), the average of the range was taken as its JRC. For comparison, the previously published equations with correlation coefficients greater than 0.98 are selected and plotted in Fig. 3 as dotted or dashed lines. The best fitted equations of this study are plotted as solid lines. As indicated by Fig. 3, the 112 data points are clustered within a thin band in between the lower and upper boundaries, showing a good concentration and an apparent and constant trend. The previously published equations proposed by Tse and Cruden [4] (Eq. (1)), Yang et al. [10] (Eq. (4)) and Yu and Vayssade [9] (Eqs. (15) and (16)) just miss the best fitted line of the data set (Eq. (E3)). As shown in Fig. 3a, they all shift towards the upper boundary, which may overestimate the JRC of a rock joint. As Fig. 3b shows, Eq. (22) by Tse and Cruden [4] and Eq. (20) by Yang et al. [10] for SF is separate from the best fitted equation (Eq. (E11)), especially at the upper part. They may underestimate the JRC. For δ in Fig. 3c, Eq. 30 by Maerz et al. [12] and Eq. (36) by Yu and Vayssade [9] run apart from the main trend of the data set at the upper part, making an obvious deviation from the best fitted equation (Eq. (E1)). The correlation given by Yu and Vayssade [9] for σ_i intends to give higher JRC values as shown in Fig. 3d.

The 112 profiles make this study derive a set of equations with the parameters in Table 1 to quantitatively estimate the JRC of a rock joint. These ten parameters reflect the irregularity and departure of a curve from a smooth and straight line and they all have been chosen for JRC estimation in the literature. The newly derived equations with correlation coefficients greater than 0.80 are given in Table 4, together with the applicable ranges of the independent variable of each equation.

It is indicated that σ_i and Z_2 have the highest correlation coefficient (0.8843) with JRC (Eqs. (E1) and (E3)). σ_i is a parameter that behaves approximately the same as Z_2. This is naturally so because for a profile where $i_{ave}=0$, we find that $\sigma_i=\arctan(Z_2)$. As defined, R_z is the measurement of the distance between the highest peak and the lowest valley of a profile. λ equals to the ratio of R_z to the projected length of the profile, measuring the overall undulation of the profile. The close correlations of R_z and λ with JRC indicate that the utmost asperity controls the JRC and then the peak shear strength of a rock joint. Other parameters (δ, R_p, R_a, R_q, and M_s) take the details of the profile and measure the overall amount of variation or dispersion from the average line (the main trend). Based on correlations in Table 4, it can be concluded that these parameters are all capable of estimating the JRC of a rock joint.

On the other hand, the parameters R_z and λ are easy to be precisely obtained for a certain profile, even with a rule. However, a well-developed computer program may be a need for the determination of other parameters (e.g., Z_2, σ_i) especially for data sets of small sampling interval. Even though today's widespread use of computers, the accumulative error in the complex calculation of these parameters is still a concern reducing the accuracy of the estimation. Considering the above, correlations of R_z and λ (Eqs. (E5)–(E8)) are highly recommended to engineering practice. Another outstanding merit of equations of R_z and λ is that these parameters are less sensitive to the sampling interval than the other features of a profile.

The power law equations in Table 4 are plotted together with the 112 data points in Fig. 4. As shown in Fig. 4 and the column "JRC^0" of Table 4, the power law equations are capable of giving a reasonable JRC value to a planar or sub-planar joint profile, while other correlations are not. It is suggested that the power law equations are used in engineering practice when estimating JRCs of planar or sub-planar joint profiles.

6. Conclusion

For decades, researchers have been made the determination of joint roughness coefficient objective and quantitative. This study reviews the advances in this field and extends the scope with a big population of joint profiles. The terms and symbols of the parameters in empirical equations are normalized by referring to the international standards. A summary is made for the existing empirical equations with discussions about their limitations. The retrievable 112 rock joint profiles are used to derive new empirical equations for JRC estimation. It is found that previously published equations may misestimate the JRC of a profile. This is mainly because of the small data set previous researchers used.

Based on 112 digitized rock joint profiles, this study proposes 15 empirical equations for JRC estimation. It is found that σ_i, Z_2, SF, R_z, λ, R_q, M_s, R_a, R_p and δ, closely correlate with JRC. Among them, σ_i and Z_2 are the best in terms of correlation coefficients. Considering the usability and accumulative errors in a complex calculation, equations with R_z and λ however, are highly recommended to engineering practice. Another suggestion is to use power law equations for planar or sub-planar joint profiles.

It should be noted that this study takes 112 rock joint profiles which are currently available in the literature. Considering the accuracy and sophistication of any empirical equation, a bigger sample population is demanded, especially for those with low JRC values.

The empirical equations proposed by this study take exclusively data points with sampling interval of 0.4 mm. As previous researchers [9,10] stated that sampling intervals might shift the relationship between JRC and statistical parameters, it is suggested that special caution should be paid when equations, especially those not taking R_z and λ but others, are used. The lack of considering sampling intervals also demands anther investigation.

R_z and λ are found to be good parameters for the estimation of JRC of rock joint due to their easy and convenient determination. The authors' concern, however, is the scale effect. As the employed profiles in this study range between 72 and 119.6 mm in length, which is a quit narrow band, the authors suggests using the equation of R_z and λ within laboratory scale. Further study taking profiles of other sizes is also demanded.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.ijrmms.2015.03.016.

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